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Magnetic Compass Dynamic Performance

Brian Bourgeois and Andrew Martinez

Abstract

This paper describes the use of a fluxgate compass to provide accurate heading information for autonomous underwater vehicles. Two sources of error are identified: steady-state bias and compass lag. Results of field tests comparing a fluxgate and a reference heading indicate the compass has excellent dynamic performance when both bias and lag compensation are applied. Plans for further laboratory testing of magnetic compass dynamic characteristics are discussed.

Keywords: AUV Navigation, heading, fluxgate compass.

1 Introduction

This paper investigates the dynamic performance of magnetic compasses as applicable to their use in autonomous underwater vehicles (AUVs). For small AUVs a magnetic compass is often the heading sensor of choice due to its small size, low cost, and low power requirements. AUVs require a heading reference for vessel navigation but also for correction of sensor data; for acoustic sensors with long slant ranges a heading accuracy of less than one degree is commonly desired. In the absence of local magnetic anomalies and locally generated magnetic fields, and with proper compensation for biases (variation and deviation), the static performance of magnetic compasses can rival that of much more expensive gyrocompasses. As an example, the KVH 103AC fluxgate compass has a rated static accuracy of ±0.5 degrees RMS (after bias compensation) as compared to ±0.5 degrees RMS times the secant of latitude (e.g., ±1.0 degrees at 60 degrees latitude) for the Robertson SKR82 gyrocompass. The cost and size of a mechanical gyrocompass is about 2 orders of magnitude greater than that of a magnetic compass.

For effective use on an AUV, a magnetic compass must be able to provide accurate heading data during dynamic vessel operations. A surface vessel is subjected to severe, often impulsive dynamics, requiring the use of more expensive gyrocompasses for accurate heading measurements. However, an AUV is not typically subject to the same magnitude of

dynamics, so the requirements for the response characteristics of the heading system can be reduced. With an AUV we can expect accelerations due to course changes, speed changes and changes in depth. We would also expect some pitch, roll and yaw motion due to the movement of the vessel's control surfaces and to water turbulence. Unfortunately, vendor specifications for magnetic compasses do not include compass performance under dynamic conditions, so it is difficult to ascertain their performance on a moving vessel.

Testing of dynamic response has been performed using the KVH 103AC compass and an Applanix POS/MV 320 system [1] on the NRL (Naval Research Laboratory) ORCA vessel [2], and the results are presented in this paper. The ORCA vessel is a 10m air-breathing semi-submersible that travels a few meters below the sea surface at a nominal speed of 10 knots. Due to its proximity to the surface and its speed, it is anticipated that the ORCA will experience dynamic motion in excess of that expected for typical AUV's, and thus provide a reasonable assessment of compass dynamic performance as applicable to an AUV. The POS/MV 320 uses a dual antenna GPS system to derive carrier-phase-based measurements of true heading. This data is coupled with that of a 3-axis IMU (inertial motion unit) to achieve heading accuracies of 0.05 degrees at sampling rates up to 100 Hz. The POS/MV is considered an absolute heading reference for this investigation.

In the next section, pertinent characteristics of magnetic compasses are discussed. In the following section, results of dynamic tests with the KVH 103AC compass are presented and interpreted. The test results compare the relative performance of the two heading sources, with the magnetic compass both uncompensated and compensated for its heading dependent phase lag. The spectral composition of signals from both systems is presented, as well as the residual error between the two systems after compensation. Finally, plans for detailed laboratory testing of magnetic compass dynamic characteristics are discussed.

2 Magnetic compass characteristics

Several different technologies are currently utilized in the manufacture of magnetic compasses, such as flux gate, self-oscillating fluxgate, variable inductance, and magnetoresistive. All of these technologies are reported by vendors to achieve heading accuracies on the order of ±0.5 degrees RMS after proper compensation. Magnetic compasses are adversely affected by numerous conditions that require compensation in order to provide accurate true north heading measurements:

- sensor vertical misalignment – to find magnetic north, a compass must measure only the horizontal components of the earth's magnetic field and exclude the vertical component. A tilt of 1 degree can result in 3 degrees or more of heading error [3]. Consequently, the compass must have an accurate vertical reference; this is easily accomplished with

much more expensive inertial systems but is challenging for packages costing $1000 or less. Leveling of the sensor element may be one of the more significant factors limiting the dynamic performance of these systems and is discussed in more detail later.

- earth's magnetic field variation – this is the position dependent variation of magnetic north from true north. This is a slowly changing value and can be readily compensated for using earth field models. Most digital magnetic compasses provide a scheme for variation correction of the output.

- own vessel deviation – this is a heading dependent effect due to ferrous metals on the vessel in the proximity of the compass. Many compass manufactures provide a compensation scheme wherein the vessel is maneuvered in a circle and a lookup table is generated for subsequent correction of heading values.

- locally generated magnetic fields – these are typically due to power carrying cables, electronic systems, etc. While these fields can be compensated for, it is generally simpler to put the compass sensing element in a magnetically *quiet* location on the vessel. Some compasses, like the KVH, provide an indication of the magnetic *quality* of the sensor location.

- motion induced eddy currents – as a metallic, albeit non-magnetic, vessel moves through the earth's magnetic field, eddy currents will be generated which will create their own magnetic fields which may subsequently induce compass errors. Compensation procedures exist for this effect, involving oscillation of a vessel's trajectory alternatively about its pitch, roll and yaw axes.

- magnetic anomalies – as an AUV travels it will pass near ferrous structures: trash, ship wrecks, man-made structures and mineral deposits. All of these will cause a local deviation in the earth's magnetic field and induce an error into the compass heading measurement. This error could be compensated for with an independent yaw measurement, and some magnetic compass vendors are now offering this feature.

There are two common approaches to magnetic compass sensor leveling – mechanical and electronic. With 2-axis systems, the sensor element must be kept physically level for accurate measurements. This is accomplished by floating the sensor in a fluid, using gimbals or both. Three axis systems can use electronic leveling with external pitch and roll sensors, and offer the added benefit of making a total vector field measurement. For both approaches, the sensor's dynamic heading accuracy will necessarily be influenced by the effectiveness of the leveling system. Performance of the leveling system is affected by the dynamic ability of the compensation method to respond to rotational accelerations and translational accelerations,

which will be incorrectly interpreted as pitch and roll. For the 3-axis sensor, it may be possible to compensate for translational acceleration errors in the pitch and roll sensors using inexpensive solid state linear accelerometers.

3 Field trials

Field testing was performed using the NRL ORCA. Magnetic heading was measured using a KVH 103AC fluxgate compass and compared with the heading from an Applanix POS/MV 320. Since the POS/MV has a heading accuracy of ±0.05 degrees, it is considered an absolute heading reference. Data was collected for 24 straight line tracks at nominal headings from 0 to 345 degrees at 15 degree intervals. Heading data from the compass and POS/MV was recorded for approximately 6 minutes for each line and resampled to 10 samples/second. Results indicate a strong agreement between the two heading sources when both heading and lag compensation are applied to the compass heading.

Raw heading data is shown in Figure 1 for a south-to-north track line with a nominal heading of 0 degrees (i.e., true north). While the dynamic behavior of both signals is quite similar, a significant bias of 17.8 degrees in the magnetic heading can be seen. This is the result of poor compensation of the compass because the standard calibration procedure could not be performed prior to the test. Fortunately, these trials were concerned with dynamic behavior of the compass and the This bias was evident in all survey lines and indicates the need for proper calibration.

Figure 2 shows the effect of removing the bias from the magnetic compass heading. Except for a significant delay in the compass heading, there is a strong similarity between the heading recorded by both the POS/MV and the compass. The RMS error without taking this lag into account is 5.3 degrees. This error can be significantly reduced by removing the compass lag.

Compass lag is a function of the internal filtering performed by the compass and the operating characteristics of the fluxgate. Since the fluxgate measures the time for its core to unsaturate, the response time is a function of external flux density, and the result is a compass lag that varies with heading. Figure 3 shows the compass lag as determined for each survey line versus nominal heading. The resulting lag is a function of heading and varies from 0.4 to 2.4 seconds. Additional field testing was conducted comparing the KVH compass and a Robertson SKR82 gyrocompass which yielded similar results for the fluxgate compass lag. Investigations are currently underway to determine repeatability and the effects of filter setting on this lag. In practice, the lags can be removed in post-processing if repeatability can be demonstrated.

In Figure 4 the compass lag has been removed and the compass and POS/MV headings
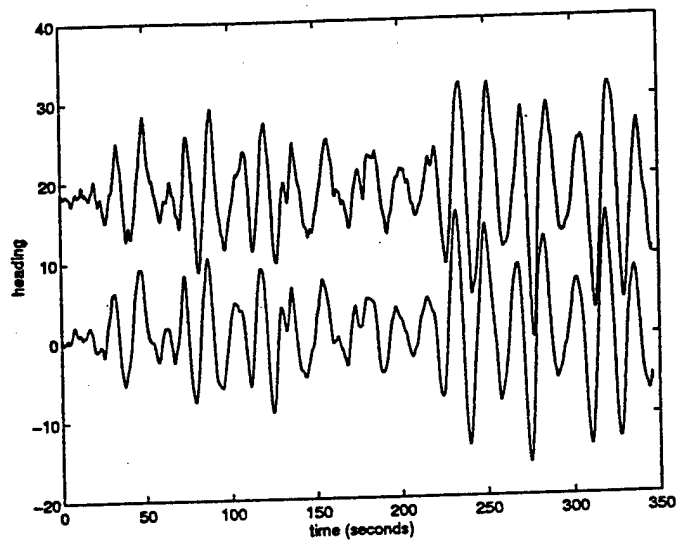
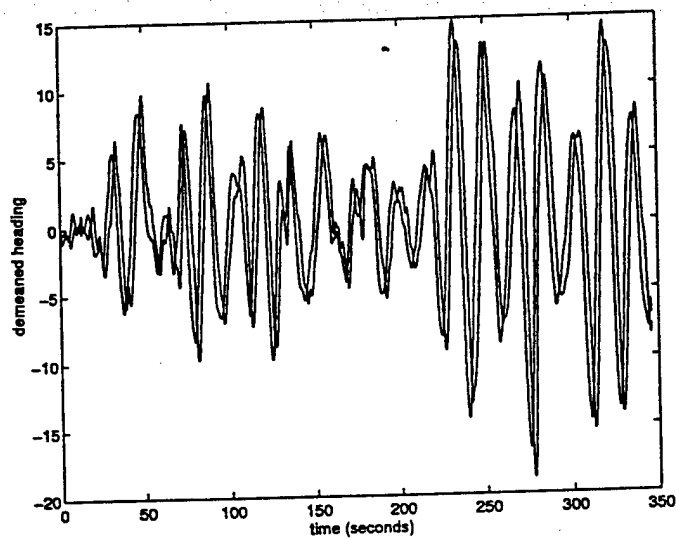Figure 1: Raw heading from POS/MV and fluxgate compass.

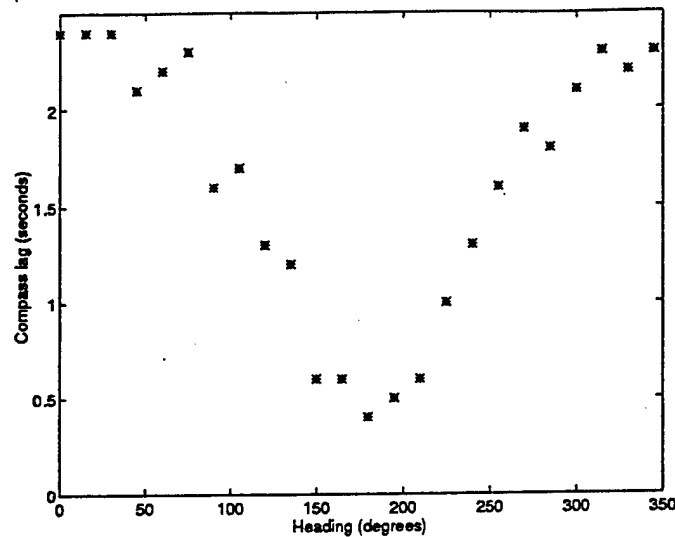Figure 2: Demeaned heading from POS/MV and fluxgate compass.

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Figure 3: Compass lag versus heading

are plotted versus time. The difference is plotted in Figure 5. The RMS error of the lag corrected compass is 1.0 degree, a reduction of 4.3 degrees from the uncorrected value. Repeating this for all track lines yields an average RMS error of 0.8 degrees and a maximum for any track of 1.0 degrees. Examining the error time series suggests that the compass heading is missing higher frequency components of the heading and these missing components make up the majority of the error.

The power spectra of the two heading time series are plotted in Figure 6. The two power spectra are identical up to 0.1 Hz and in close agreement up to 0.15 Hz. The majority of the heading dynamics are below 0.1 Hz for this particular survey; for this bandwidth the compass gives very reasonable results. Because of this, additional filtering of the compass heading beyond a simple time shift produced very little improvement of the compass heading estimate. Current experimentation includes collecting data with broader band dynamics to fully quantify and compensate for the effects of the compass filter.

4   Conclusions and Future Work

Two principle sources of error in compass heading were identified in field testing: bias and lag. When both are fully compensated the dynamic performance of the compass is excellent. Additional work is needed in determining the effects of the compass filter on both lag and bandwidth constraints observed in these trials.
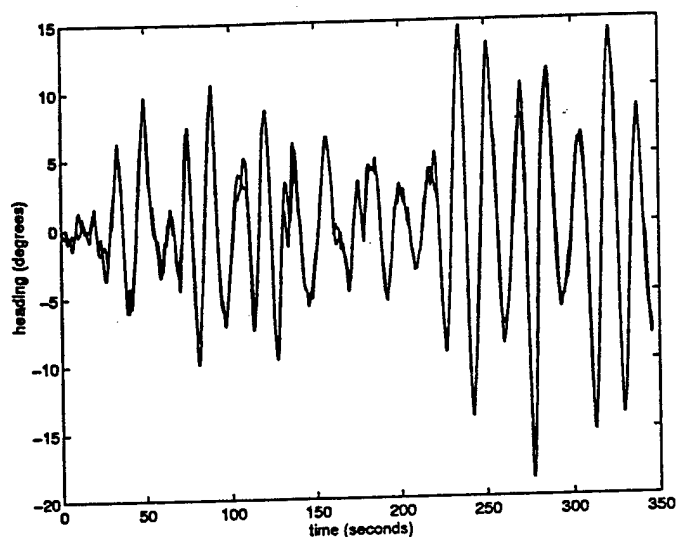
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Figure 4: POS/MV and lag-corrected fluxgate heading.
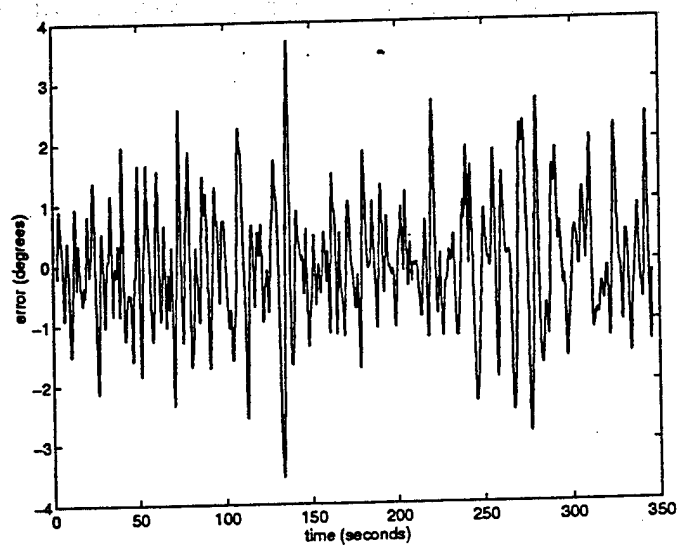

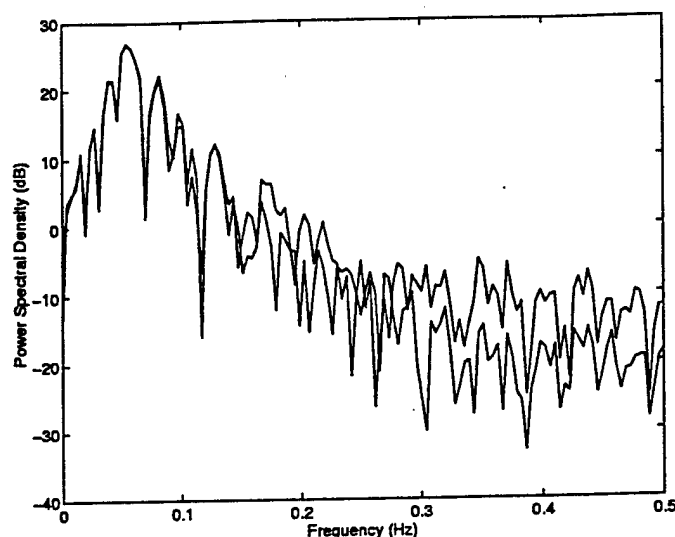Figure 5: The lag-corrected compass error.

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Figure 6: Power spectral densities of POS/MV and fluxgate compass.

To further investigate the performance of the KVH 103AC and other magnetic compasses under more controlled conditions, a test stand is being constructed. The test stand has the compass, the POS/MV IMU and the center point of the dual GPS antennas mounted on the same longitudinal line on a wooden platform. The IMU and the processors are located as far away from the compass as practical to minimize magnetic interference. For testing the test stand will be taken to a magnetically quiet area away from buildings and other structures. The built-in filtering and variation compensation in the compass will be disabled to determine if they are the cause of the heading dependent time lag and bandwidth constraints observed in the previously collected data. Stationary tests will be performed at multiple headings to determine the stationary noise characteristics of the systems. Dynamic tests will include step inputs and controlled oscillations at various headings with the compass leveled. Similar tests will be performed with the compass inclined to evaluate any degradation due to the fluid leveling system of the 2-axis sensor of the compass. Finally, vehicle drive-bys will be conducted to investigate the ability to use an independent yaw input to compensate for external anomalies.

Acknowledgments

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References

[1] Applied Analytics Corporation, *POS/MV 320 Version 1 Installation and Operation Manual*, Nov. 1995.

[2] B. Bourgeois, M. Kalcic, and M. Harris, "ORCA - oceanographic remotely controlled automaton," *The Hydrographic Journal*, , no. 79, pp. 3–11, Jan. 1996.

[3] KVH Industries, Inc., *KVH C100 Compass Engine Technical Manual*, 1991.